Overview of the TOPEX/POSEIDON Platform Harvest Verification Experiment

Charles S. Morris, Stephen J. DiNardo and Edward J. Christensen

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

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Abstract

An overview is given of the in situ measurement system installed on Texaco's Platform Harvest for verification of the sea-level measurement from the TOPEX/POSEIDON satellite. The pre-launch error budget suggested that the total root mean square (RMS) error due to measurements made at this verification site would be less than four centimeters. The actual error budget for the verification site is believed to be within the original specifications. However, evaluation of the sea-level data from three measurement systems at the platform has resulted in unexpectedly large differences between the systems. Comparison of the sea-level measurements has led to a better understanding of the problems of measuring sea level in relatively deep ocean, As of December 14, 1993, the Platform Harvest verification site has successfully supported 46 TOPEX/POSEIDON overflights.

1. Introduction

TOPEX/POSEIDON is a satellite mission that uses altimetry to make precise measurements of sea level; the primary goal is study of global ocean circulation. This mission is jointly conducted by the United States' National Aeronautics and Space Administration (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES). A description of the satellite instruments and mission is given by Zieger et al. (this issue),

TOPEX/POSEIDON was launched on August 10, 1992, and was placed in its operational orbit through a series of maneuvers spanning approximately six weeks. The first complete 9.9 day cycle of operational data (Cycle 1) commenced September 23. To date, TOPEX/POSEIDON is providing researchers with the most accurate sea-level measurements ever obtained from an altimetric satellite. To verify the performance of the satellite system, NASA and CNES developed a Joint Verification Plan (Christensen and Menard, 1992) that included contributions from the scientific community and the TOPEX/POSEIDON Project, A major component of this effort is "on-site" verification: the comparison of the satellite data with an extensive series of in situ measurements made at a verification site. Both NASA and CNES instrumented separate verification sites. The CNES verification site was located at Lampione, a small islet 18 kilometers (km) west of Lampedusa Island in the Mediterranean Sea. The NASA verification site is an oil platform off of Point Conception, California, This paper and the associated papers in this special issue will focus on the experiment design, implementation and results obtained at the NASA verification site.

This is not the first time on-site verification has been conducted for satellite altimeters. Previous verification work has been performed for SEASAT (Kolenkiewicz and Martin, 1982) and ERS- 1 (Scharroo et al., 1991; Wakker et al, 1992). In terms of the absolute accuracy required, the TOPEX/POSEIDON on-site verification effort is the most ambitious activity of this type ever attempted,

2. On-Site Verification and the Closure Analysis

The purpose of on-site verification is to collect, in a single location, the in situ data necessary to independently verify the performance of the TOPEX/POSEIDON measurement system. From these data, an estimate is made of the system bias, usually expressed in terms of altimeter bias - that is - the difference between the expected altimeter to ocean distance and the actual distance measured by the altimeter. Bias is of interest when more than one altimeter's data are compared to evaluate long-term trends in the ocean and, also, as a measure of our understanding of the operation of the altimeter and the processing of the data. Of greater importance is the temporal change in the bias (called bias drift) which, if it were significant, could have a serious impact on the scientific results.

On-site verification requires an independent measure of the altimeter to ocean distance. To obtain this independent value, in situ sea level must be accurately tied to the same reference frame as the satellite. This is accomplished by combining a number of measurements obtained using different techniques. First, the position of the satellite over the verification site must be determined to within a few centimeters in the vertical by applying orbit determination techniques to laser and other tracking data, This establishes the position of the satellite in the reference frame of the lasers. The location of the verification site relative to the lasers is estimated using Global Position System (GPS) receivers. Finally, vertical measurements are made from the GPS antenna to the sea level measurement instruments. This ties the verification site sea-level measurements to the same reference frame as the lasers and the satellite. An estimate of the satellite/sea-level distance is obtained using triangulation and is compared to the altimeter measurement. We call this analysis “closure.” This concept is illustrated in Figure 1 and an in-depth discussion is provided by Christensen et al. (1989).

3. **Verification Site Selection**

Several factors must be considered when selecting a verification site. A primary requirement is that it be located far enough from land to avoid contaminating the altimeter signal, In addition, the site itself must be small enough so that it will not affect the altimeter’s response.

The logical choices for a verification site are limited to a small island or an oil platform. An evaluation of several potential locations for the NASA verification site, including Bermuda, oil platforms in the Gulf of Mexico, and oil platforms off of California, was made. Several criteria were used in the selection process, including the following:

- o the available laser coverage
- o anticipated accuracy of the in situ observations
- **o** logistical considerations
- o cost

The decision was made to instrument an oil platform located off of Point Conception, California. Several oil platforms were then considered. Texaco's Platform Harvest, located 11 kilometers (km) south-southwest of Point Arguello and 19.5 km west of Point Conception, California, was finally chosen as the NASA verification site (see Figure 2). The selection was based on the excellent laser coverage (see Figure 3) and logistical considerations. In March 1991, a Memorandum of Understanding was signed between Texaco USA, Inc., and JPL permitting the installation of instrumentation at the platform,

4. Verification Site Instrumentation

The verification work performed at Platform Harvest is a collaborative effort among the National Oceanographic and Atmospheric Administration/National Ocean Service (NOAA/NOS), the University of Colorado (CU), and the Jet Propulsion Laboratory (JPL). The design and installation of the instrumentation and equipment used in this experiment had to meet various constraints, some of which conflicted with one another. These included satisfying the observational requirements (e.g., sky visibility), oil platform safety requirements, platform space requirements, and the need to conduct the experiment without interfering with oil platform operations. Table 1 summarizes the major milestones of the installation of the verification instrumentation at Platform Harvest.

The instrumentation installed at Platform Harvest was selected to measure those parameters required for the closure anal ysis. These instruments are summarized in Table 2 and their relative location on the platform is illustrated in Figure 4. Because the primary goal of the experiment was to measure sea level, three different types of sea-level measurement systems were installed to monitor the level of the ocean. NOAA/NOS supplied a Next Generation Water Leveling Measuring System (NGWLMS) that includes two water-level sensors: a self-calibrating acoustic device with an echo-timing receiver, and a back-up pressure transducer/nitrogen bubbler combination. Both of these systems provide sea-level estimates averaged over 181 seconds once every six minutes. In addition, the acoustic system has the optional capability to record sea level in a high-rate or tsunami mode which produces a sea-level measurement every two seconds. CU provided the third system consisting of three pressure transducers. Two pressure transducers are mounted below the water and the third measures atmospheric pressure. This arrangement permits the two submerged pressure transducers to be intercompared. The third transducer serves as a back-up to the NOAA/NOS barometer for measuring atmospheric pressure. The CU system provides sea-level estimates about once-per-second during satellite overflights and approximately every two minutes at other times. The NOAA/NOS and CU systems are discussed in detail by Gill et al. (this issue) and Kubitschek et al. (this issue), respectively.

The platform's location relative to the laser sites is obtained by operating a Turbo Rogue GPS receiver at the platform. In addition, the GPS receiver also provides an estimate of the total electron content (TEC) through a vertical column above the platform, The derived TEC value is one of the checks made on the ionospheric correction, which is applied to the altimeter measurement. Further description of the GPS receiver is given by Purcell et al. (this issue).

Although the location of Platform Harvest in relation to land does not affect the altimeter signal, it was anticipated that land would contaminate the passive microwave Topex Microwave Radiometer (TMR) observations during TOPEX/POSEIDON overflights of the platform, because of TMR's significantly larger footprint. The primary purpose of TMR is to provide a columnar atmospheric water-vapor estimate so that the altimeter observations can be corrected for the affects of water vapor. At the platform, an upward-looking water vapor radiometer (WVR) provides an alternate measurement of water vapor. A JPL J-Series WVR (see Keihm and Ruf, this issue) is mounted near the platform's heliport to perform this task.

Ancillary measurements of relative humidity, barometric pressure, water temperature, water conductivity, and air temperature are made by NOAA/NOS instrumentation. Some of these measurements, such as the barometric pressure, water temperature and conductivity, are crucial to the proper reduction of the pressure transducer sea-level data (Kubitschek et al., this issue).

The computers associated with the verification instrumentation at the platform are housed in a small custom-made equipment shed. Other equipment in the shed provide clean power and communications via satellite (NOAA/NOS data only) and cellular telephone. The importance of providing clean power by using an uninterruptible power supply (UPS) cannot be overstated. The platform power is supplied by turbine generators and momentary outages occur when the configuration of on-line generators is modified. In addition, longer outages sometimes occur during specific platform operations. Use of cellular telephone and satellite communication allows the verification experiment to be totally independent of the platform's microwave telephone link. Remote, real-time monitoring and configuration of each system computer is possible,

Although the initial satellite overflights had Verification Team personnel at the platform to monitor the instrumentation, data collection during the overtlights was soon monitored remotely. Most of the data collection systems are automatic, requiring no manual intervention except to download the data, Data transmission off the platform is even handled automatically for the GPS and NOAA/NOS systems.

5. Verification Site Error Budget

Table 3 presents the prelaunch error budget for the NASA verification site. The errors specified are for a single overflight. The error budget was derived from calculation (i.e., thermal expansion), measurement (i.e., platform sway), and expert opinion (i.e., GPS and sea-level measurement accuracy). Potential errors included both fixed and variable measurement errors, as well as errors resulting from changes in the platform. For instance, the location of the oil platform relative to the lasers is dependent on the accuracy of the GPS measurements. It is estimated that there is the potential for a fixed error (offset or bias) of up to 2.0 cm. However, the variable error (from one overflight to the next) for the tie between the lasers and the platform is expected to be negligible.

There is the potential for vertical changes resulting from platform sway. The motion of the platform has been a significant concern since Platform Harvest was selected as the NASA verification site, Sitting in 670 feet of water, the platform is nearly as large as the Eiffel Tower.

Wind and wave action can produce a noticeable sway. The critical issue for verification is the effect of the sway on the vertical location of the verification instruments. **CU** has conducted an experiment at Platform Harvest using an accelerometer designed to measure vertical acceleration and, thus, motion (Johnson, 1994), This experiment occurred during high wind (30+ reps) and wave (up to 12 meters) conditions. The resulting vertical motion was about one centimeter. During less severe conditions, the motion was found to be considerably less. Under "normal" conditions, the motion of the platform is expected to be 0.5 cm or less,

The vertical survey, which ties the GPS antenna to the sea-level instruments, also may have a fixed measurement error and a variable error due to thermal expansion. This vertical distance of about **45** meters is difficult to obtain because the measurement must be made down narrow stairways that **are** exposed to the wind, and the platform itself is swaying, which affects the leveling of the surveying instruments. Despite these problems, **NOAA/NOS** personnel surveyed this vertical distance with an estimated accuracy of four millimeters.

There are a number of measurement errors associated with the determination of sea level, The largest was originally thought to be the variable error resulting from the spatial variability of the ocean within the altimeter footprint. This **error**. results from comparing a point in situ measurement with the altimeter observation averaged over a several-kilometer footprint. The cross-track **geoid** error results from overflight-to-overflight variations **in** the satellite's groundtrack, which is maintained to within $\pm$ 1.0 km, and from uncertainties in the **geoid** in the vicinity of the oil platform. It is expected that this potential error will be reduced as additional overflight data are obtained.

Of particular note is the "instrument noise" error. Prior to launch, the consistent measurement of sea level was not considered to be a problem; an accuracy of better than one centimeter was expected. Analysis of the sea-level data from the verification site, even after calibration for instrument drift, led to the discovery of inconsistencies between the different sea-level data sets. This problem is illustrated in Figure 5, which displays the differences between the different tide-gauge sea-level measurements at the time of the TOPEX/POSEIDON overflights. These differences, at times, are many centimeters. As these sea-level data are collected continuously, it has been possible to study the response of the different tide gauges in detail. The magnitude of these differences varies on time scales ranging from hours to weeks. As discussed by Parke and Gill (this issue), at least a some of these inconsistencies are now understood. However, the 1.0 cm variable error assumed for instrument noise may still be underestimated.

Including additional overflights will reduce the variable errors, but not the fixed errors. After consideration of the potential error sources related to the in situ measurements at the verification site, the expected accuracy of the in situ measurements for one overflight is better than 3.5 cm. When the estimated errors in the altimeter measurement and altimeter orbit (Table 4) are included, the projected error in comparing the altimeter-derived height with the in-situ-derived height is 5.2 cm for a single overflight. This error decreases as the number of overflights increases (see Table 5).

6. Discussion

Although every effort was made to quantify the expected observational errors at the verification site prior to the installation of the instrumentation (and satellite launch), we were surprised by the problems of measuring sea level in (relatively) deep water. Fortunately, the redundant systems installed at the platform provided an opportunity to study the effects and estimate a correction for the measured sea-level values (see Parke and Gill, this issue).

Although we don't have a direct estimate of the actual error of the combined in situ measurements at the verification site, the altimeter bias closure results do provide an idea of whether the prelaunch error budget was realistic. Christensen et al. (1994) has obtained a preliminary estimate for the bias of the NASA altimeter of -14.7 cm $\pm$ 2.1 cm from 21 TOPEX/POSEIDON overflights. The negative value indicates that the NASA altimeter is measuring short (higher sea level) in comparison to the in situ measurements, The consistency of these results suggests that the error budget for the verification site measurements is reasonable.

There have been the expected problems experienced by any in situ data collection system, including some data loss. However, as of December 14, 1993, the Platform Harvest verification site has successfully supported 46 overflights of the TOPEX/POSEIDON satellite. An in-depth discussion of the first 30 overflights can be found in Morris (1994).

The TOPEX/POSEIDON Science Verification Team gratefully acknowledges the assistance and cooperation of Texaco and, in particular, the personnel of the Ventura, California office and on Platform Harvest (Texaco and contractors), Without their support and advice, this work and its success would not have been possible. Special thanks go to Richard Gunder of VECO for assisting us many times at the platform when we were unable to be there. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Figure Captions

Figure 1 **The** concept of on-site verification. The closure analysis compares the altimeter-to-ocean distance estimated from in-situ measurements with the altimeter measurement,

Figure 2 The location of the NASA verification site off the coast of the California coast. The ticked line shows the ascending TOPEX/POSEIDON groundtrack and the circle illustrates an idealized altimeter measurement footprint.

Figure 3 Laser coverage for the NASA verification site overflights.

Figure 4 Location of the verification instrumentation on Platform Harvest.

Figure 5 a) Sea level at Platform Harvest during the satellite overflights as a function of TOPEX/POSEIDON çycle. Note that sea level is measured downward (an overflight during a high tide = low value). b) Difference between NOAA/NOS acoustic and CU pressure transducer sea level at the overflight times, c) Difference between NOAA/NOS acoustic and NOAA/NOS NO_2 bubbler sea level at the overflight times, and d) Difference between the NOAA/NOS $N0_2$ bubbler and CU pressure transducer sea level at the overflight times.

Table 1

Installation of In Situ Verification Instrumentation on Platform Harvest Significant Events

	1990
May	Platform Harvest selected as the NASA Verification Site.
August	One week Platform Experiment testing the feasibility of operating a GPS receiver and water vapor radiometer at the platform.
December	First vertical platform survey between the GPS and sea level reference point conducted by NOAA/NOS.
	1991
March	MOU signed between Texaco and JPL.
June	Walkway installed to permit access to one of the sea level risers.
December	Steel risers, which house the sea level instrumentation, are installed by divers.
	1992
April	JPL equipment shed is installed.
May	NOAA/NOS and CU Sea level instrumentation commences operation. NOAA/NOS ancillary instrumentation is installed. NOAA/NOS performs the second vertical platform survey.
June	GPS receiver is installed.
July	Water vapor radiometer begins taking data.
August	TOPEX/POSEIDON is launched on the 10th.
September	First TOPEX POSEIDON overflight occurred on the 24th.
	1993
December	Verification site successfully collects data for the 46th consecutive TOPEX/POSEIDON overflight on the 14th.

Table 2

NASA Verification Site Instrumentation

Instrument	Parameter	Responsible
Sea Level Instrumentation	Sea Level	
NGWLMS* - Acoustic		NOAA/NOS
NGWLMS* - N_2 Bubbler		NOAA/NOS
Pressure Transducers		Univ. of Colorado
Rogue Global Positioning System (GPS) Receiver	Position and Columnar Total Electron Content	JPL (Sec. 335)
Water Vapor Radiometer	Columnar Water Vapor	JPL (Sec. 383)
Barometer	Atmospheric Pressure	NOAA/NOS
Hygrometer	Relative Humidity	NOAA/NOS
Thermometer	Atmospheric Temperature	NOAA/NOS
Ancillary Ocean Instrumentation	Water Temperature	NOAA/NOS
	Water Conductivity	NOAA/NOS

•NGWLMS = Next Generation Water Level Measurement System

TABLE 3

Pre-Launch Verification Site Error Budget

Source	Fixed (Centimeters)	Variable
GPS Survey		
Survey Error	2.0	0.0
Platform Sway	0.O	0.5
Thermal Expansion of Platform (below water line)	0,0	0.5
Other Vertical Changes	0.0*	0.0
Platform Survey		
Survey Error	0.5	0.0
Thermal Expansion of Platform (above water line)	0.0	1.0
Sea Level Measurement		
Instrument Zero	0.0	0.0
Instrument Noise	0.0	1.0
Geoid Crosstrack Variability	0.0	0.5
Ocean Spatial Variability	0.0	2.0
RSS Total	**2.06**	**2.60**
RSS Total (Fixed+Variable):	**3.32**	

* At the time of the GPS survey. May change (increase) between surveys.

TABLE 4

Laser Tracking and Altimetry Errors For a Single Overflight

Source	RSS Error (Centimeters) Fixed	Variable
Instrument		2.0
Dry Tropospheric Correction	0.0	0.7
Wet Tropospheric Correction	0.5	0.5
Ionosphere Correction	1.0	0.5
EM-Bias	1.4	1.4
Skewness	0.0	1.0
Total Altimetry Error	**1.8***	**2.8**
Orbit Height Error from Laser Tracking	2.0	1.0
RSS Total	**2.69**	**2.97**

* Does not include altimeter bias.

TABLE 5

Expected Error as a Function of Number of Overflights

Number of Overflights	Total RMS Error (centimeters)*	Variable Error Contribution (cm)*
1	5.2	3.9
3	4.9	3.6
5	4.6	3.1
10	4.1	2.3
20	3.8	1.7
30	3.7	1.4

*Includes contributions from the in situ measurements, laser tracking and altimetry. The method includes estimation of bias and bias drift,

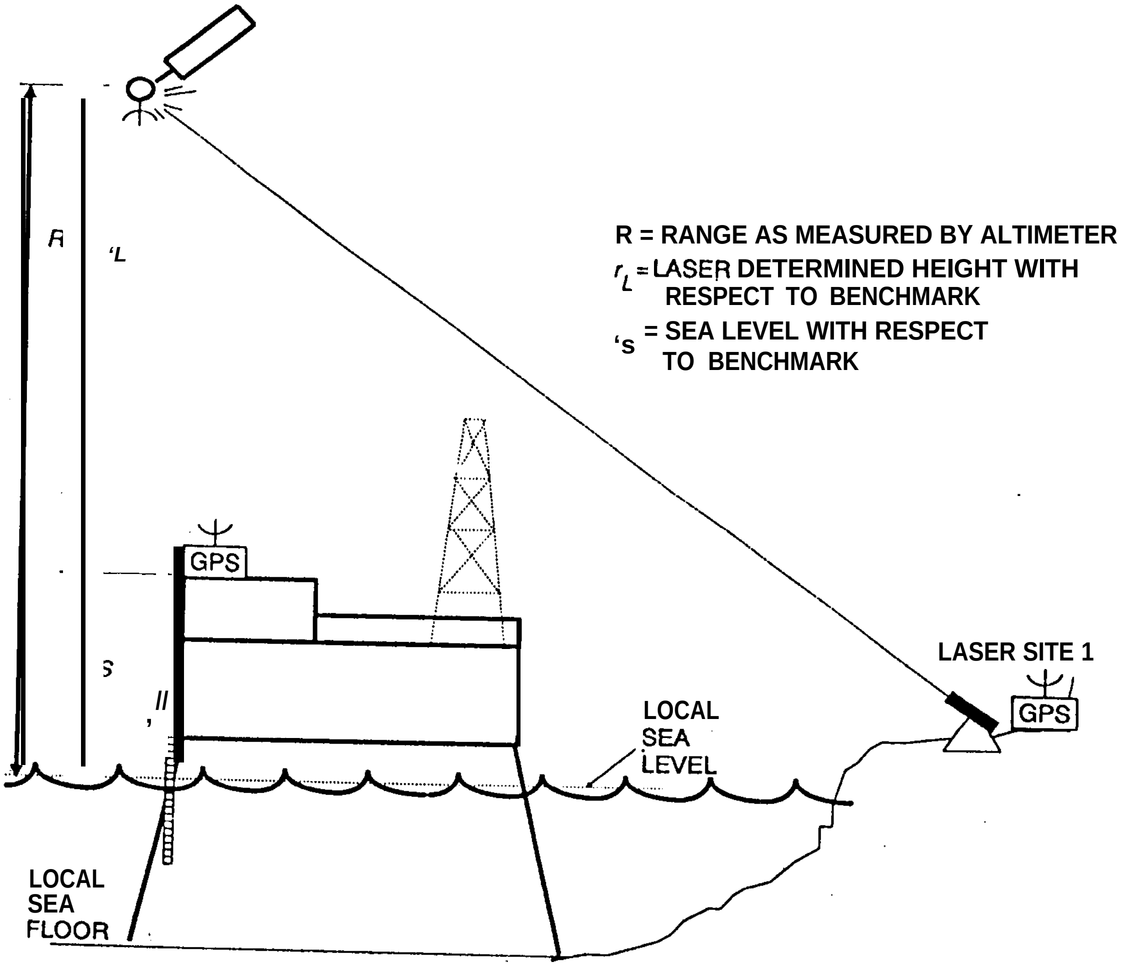

R = RANGE AS MEASURED BY ALTIMETER
r L = LASER DETERMINED HEIGHT WITH RESPECT TO BENCHMARK
'S = SEA LEVEL WITH RESPECT TO BENCHMARK
GPS
LASER SITE 1
GPS
LOCAL SEA LEVEL
LOCAL SEA FLOOR

Figure 1

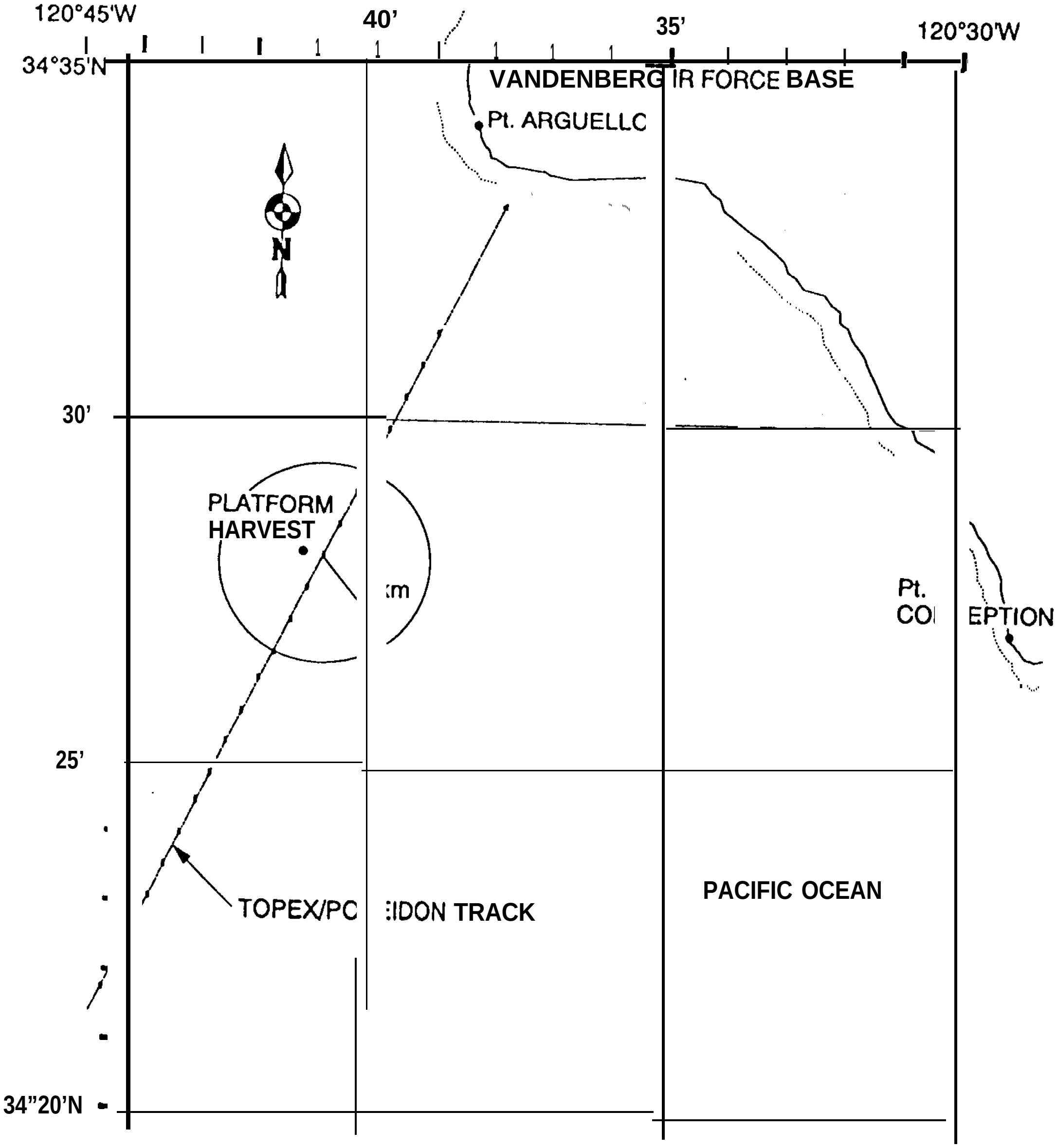
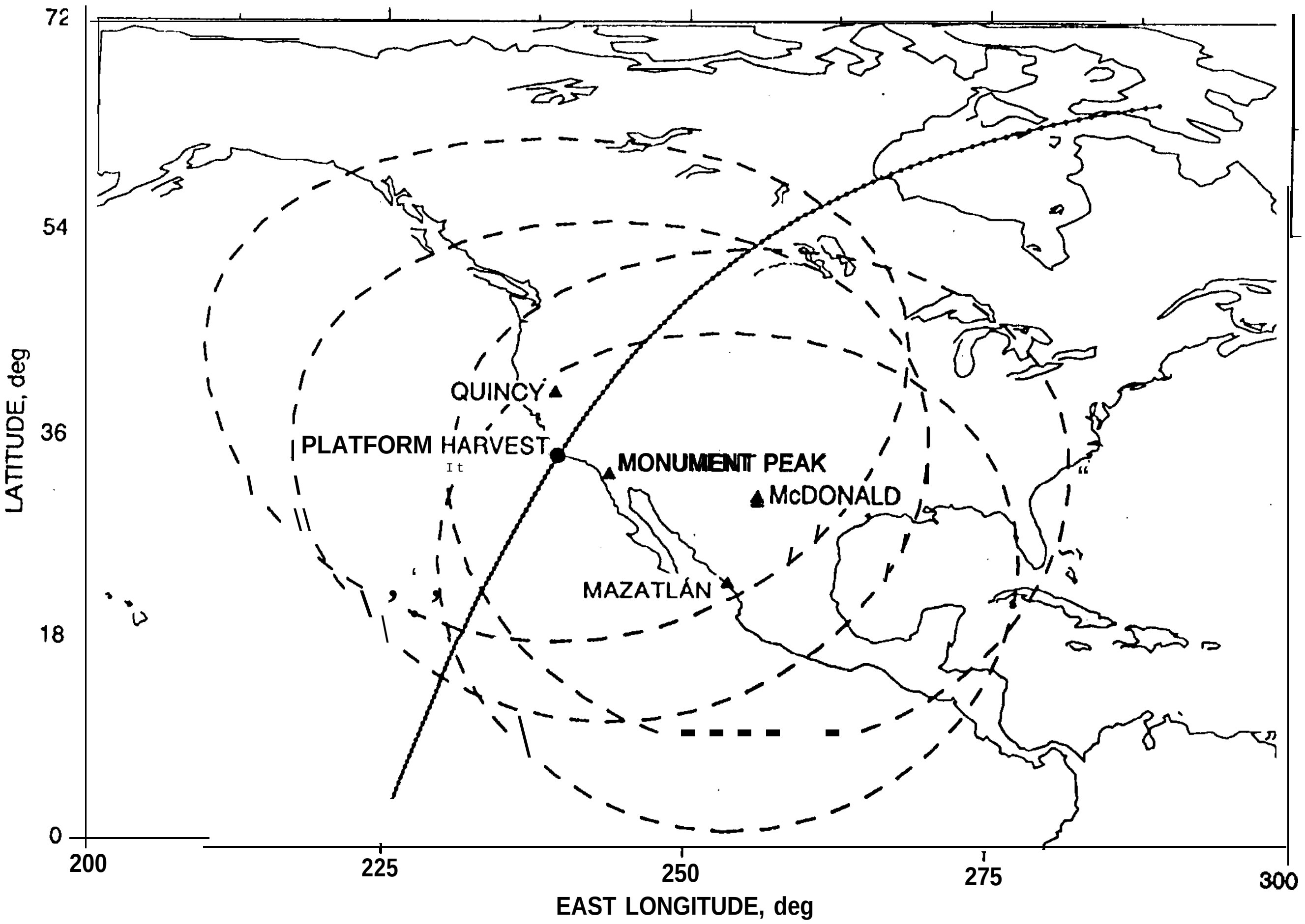

120°45'W
40'
35'
120°30'W
34°35'N
VANDENBERG IR FORCE BASE
Pt. ARGUELLC
N
30'
PLATFORM
HARVEST
:m
Pt.
COI EPTION
25'
TOPEX/PC :IDON TRACK
PACIFIC OCEAN
34"20'N

Figure 2



72
54
36
18
0
200
225
250
275
300
LATITUDE, deg
EAST LONGITUDE, deg
QUINCY
PLATFORM HARVEST
MONUMENT PEAK
McDONALD
MAZATLÁN

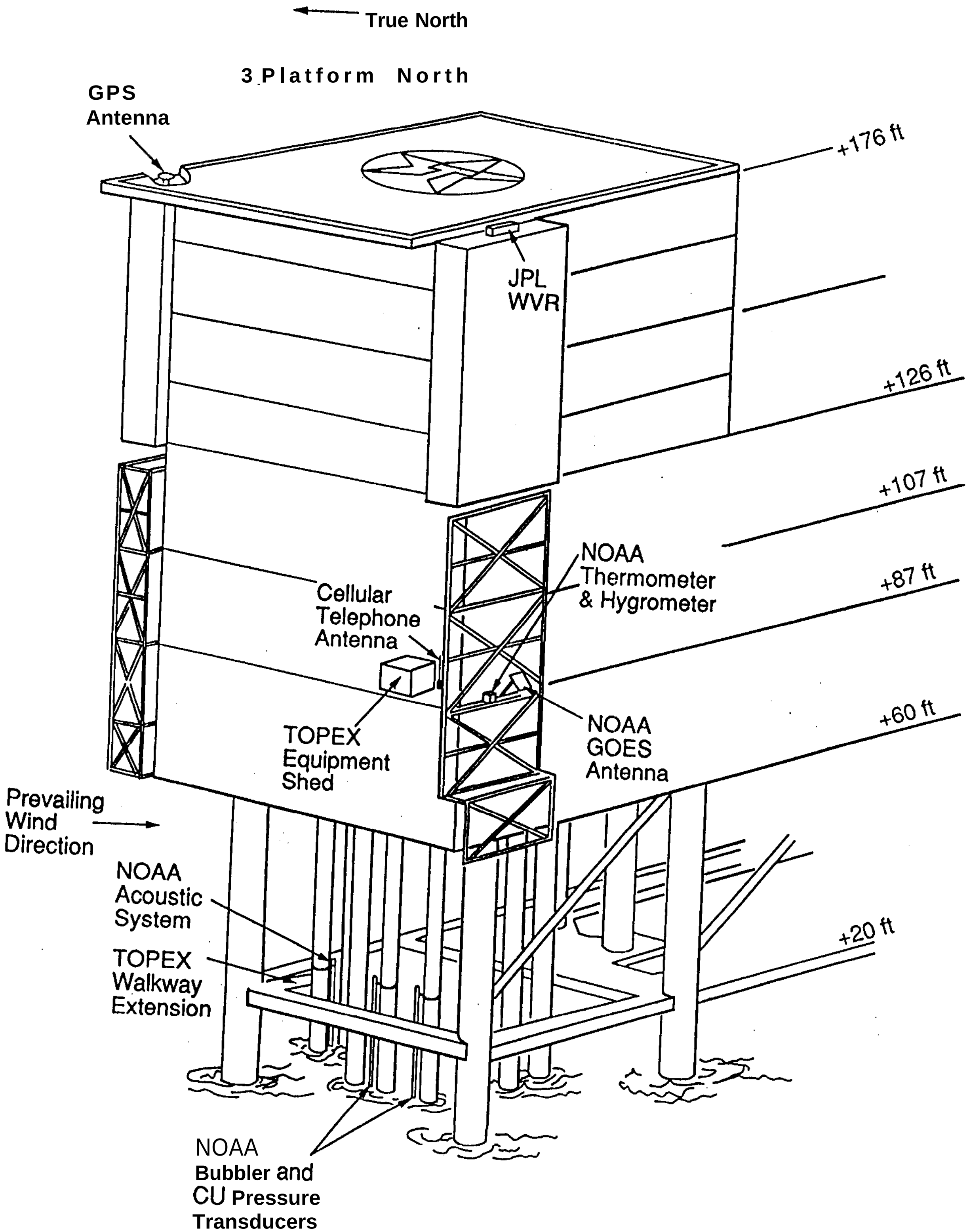
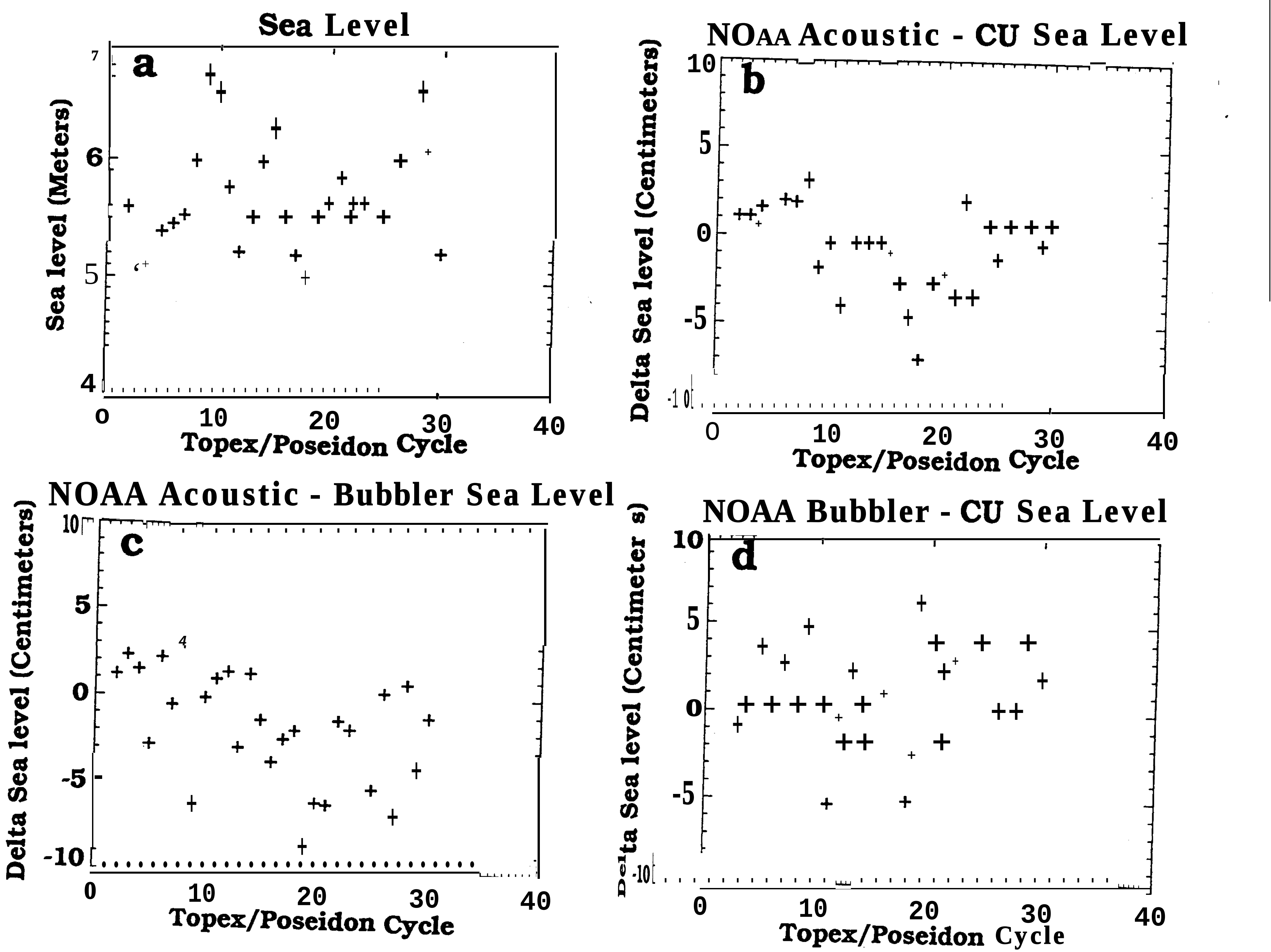

True North
3 Platform North
GPS
Antenna
+176 ft
JPL
WVR
+126 ft
+107 ft
NOAA
Thermometer
& Hygrometer
+87 ft
Cellular
Telephone
Antenna
TOPEX
Equipment
Shed
NOAA
GOES
Antenna
+60 ft
Prevailing
Wind
Direction
NOAA
Acoustic
System
TOPEX
Walkway
Extension
+20 ft
NOAA
Bubbler and
CU Pressure
Transducers

FIGURE 4



Sea Level
a
Sea level (Meters)
Topex/Poseidon Cycle
NOAA Acoustic - CU Sea Level
b
Delta Sea level (Centimeters)
Topex/Poseidon Cycle
NOAA Acoustic - Bubbler Sea Level
c
Delta Sea level (Centimeters)
Topex/Poseidon Cycle
NOAA Bubbler - CU Sea Level
d
Delta Sea level (Centimeter s)
Topex/Poseidon Cycle

FIGURE 5